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From Quark Matter to Strange Machos

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Abstract

This paper gives an overview of the properties of all possible equilibrium sequences of compact strange-matter stars with nuclear crusts, which range from strange stars to strange dwarfs. In contrast to their non-strange counterparts, –neutron stars and white dwarfs–, their properties are determined by two (rather than one) parameters, the central star density and the density at the base of the nuclear crust. This leads to stellar strange-matter configurations whose properties are much more complex than those of the conventional sequence. As an example, two generically different categories of stable strange dwarfs are found, which could be the observed white dwarfs. Furthermore we find very-low-mass strange stellar objects, with masses as small as those of Jupiter or even lighter planets. Such objects, if abundant enough in our Galaxy, should be seen by the presently performed gravitational microlensing searches.

1 Introduction

The theoretical possibility that strange quark matter may be absolutely stable with respect to iron, that is, the energy per baryon is below 930 MeV, has been pointed out by Bodmer (1971), Terazawa (1979), and Witten (1984). This so-called strange

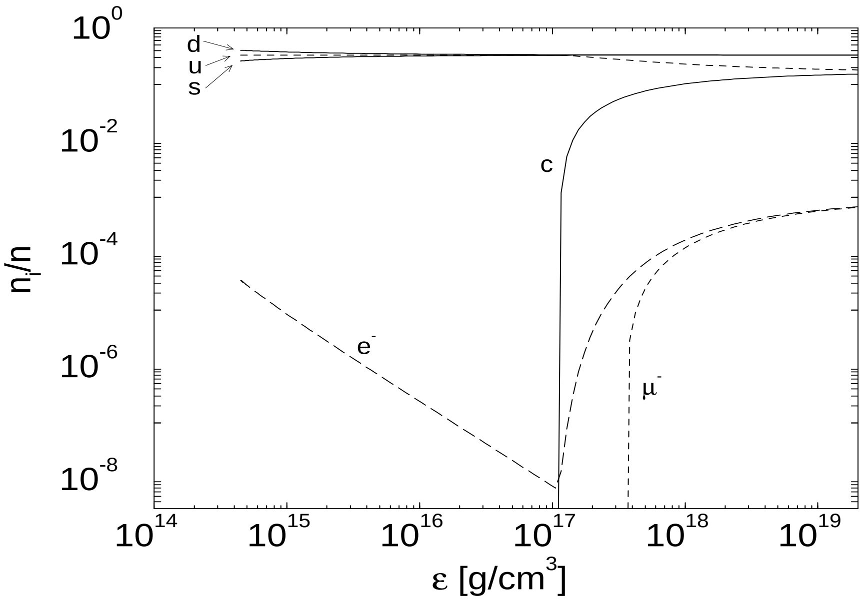

Figure 1: *Relative densities of quarks and leptons, n_i/n, where n denotes the total quark density, in cold, beta-stable, electrically charge neutral quark-star matter as a function of energy density ($B^{1/4} = 145$ MeV) (Kettner et al, 1995a).*

matter hypothesis constitutes one of the most startling possibilities of the behavior of superdense nuclear matter, which, if true, would have implications of fundamental importance for cosmology, the early universe, its evolution to the present day, astrophysical compact objects, and laboratory physics (for an overview, see Madsen and Haensel (1991), and Table 1). Even to the present day there is no sound scientific basis on which one can either confirm or reject the hypothesis, so that it remains a serious possibility of fundamental significance for various phenomena.

On theoretical scale arguments, strange quark matter is as plausible a ground state as the confined state of hadrons (Witten, 1984; Farhi and Jaffe, 1984; Glendenning, 1990) Unfortunately it seems unlikely that QCD calculations will be accurate enough in the foreseeable future to give a definitive prediction on the stability of strange matter, and one is left with experiment, Table 2, and astrophysical tests, as performed here, to either confirm or reject the hypothesis.

One striking implication of the hypothesis would be that pulsars, which are conventionally interpreted as rotating neutron stars, almost certainly would be rotating strange stars (strange pulsars) (Witten, 1984; Haensel, Zdunik, and Schaeffer, 1986; Alcock, Farhi, and Olinto, 1986; Glendenning, 1990). Part of this paper deals with an investigation of the properties of such objects. In addition to this, we develop the complete sequence of strange stars with nuclear crusts, which ranges from the compact members, with properties similar to those of neutron stars, to white dwarf-like objects (strange dwarfs), to planetary-like strange matter objects, and discuss their stability against acoustical vibrations (Glendenning, Kettner, and Weber, 1995a,b; Kettner, Weber, Weigel, and Glendenning, 1995b). The properties with respect to which strange-matter stars differ from their non-strange counterparts are discussed,

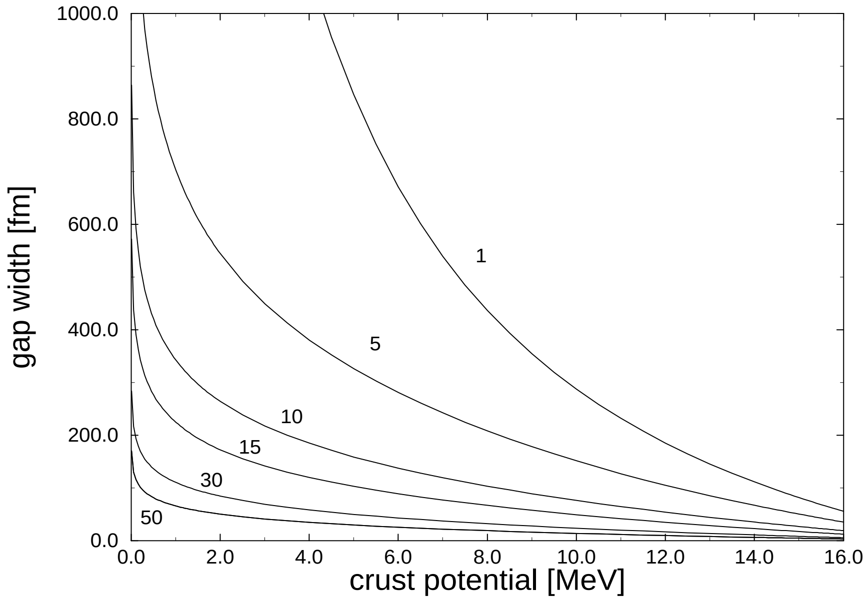

Figure 2: *Gap width, $R_{\rm gap}$, versus electrostatic crust potential, $eV_{\rm crust}$. The labels refer to temperature (in MeV).*

and observable signatures of strange stars are pointed out.

2 Quark-lepton composition of strange matter

The relative quark/lepton composition of quark-star matter at zero temperature is shown in Fig. 1. All quark flavor states that become populated at the densities shown are taken into account. (Strange and charm quark masses of respectively 0.15 GeV and 1.2 GeV are assumed.) Since stars in their lowest energy state are electrically charge neutral to very high precision (Glendenning, 1985), any net positive quark charge must be balanced by leptons. In general, as can be seen in Fig. 1, there is only little need for leptons, since charge neutrality can be achieved essentially among the quarks themselves. The concentration of electrons is largest at the lower densities of Fig. 1 due to the finite s-quark mass which leads to a deficit of net negative quark charge, and at densities beyond which the c-quark state becomes populated which increases the net positive quark charge.

3 Nuclear crusts on strange stars

The presence of electrons in strange quark matter is crucial for the possible existence of a nuclear crust on such objects. As shown by Alcock, Farhi, and Olinto (1996), and Kettner, Weber, Weigel, and Glendenning (1995a), the electrons, because they are bound to strange matter by the Coulomb force rather than the strong force, extend several hundred fermi beyond the surface of the strange star. Associated with this electron displacement is a electric dipole layer which can support, out of contact with

Phenomenon	References
Centauro cosmic ray events	Chin et al. (1979), Bjorken et al. (1979), Witten (1984)
High-energy gamma ray sources	Jaffe (1977), Baym et al. (1985)
Strange matter hitting the earth:	
strange meteors	De Rújula et al. (1984)
nuclearite-induced earthquakes	De Rújula et al. (1984)
strange nuggets in cosmic rays	Terazawa (1991,1993)
Strange matter in supernovae	Michel (1988), Benvenuto et al. (1989), Horvath et al. (1992)
Strange star (pulsar) phenomenology	Alcock et al. (1986), Haensel et al. (1986), Alcock et al. (1988), Glendenning (1990), Glendenning et al. (1992)
Strange dwarfs	Glendenning et al. (1995a), Glendenning et al. (1995b)
Strange planets	Glendenning et al. (1995a), Glendenning et al. (1995b)
Burning of neutron stars to strange stars	Olinto (1987), Horvath et al. (1988), Frieman et al. (1989)
Gamma-ray bursts	Alcock et al. (1986), Horvath et al. (1993)
Cosmological aspects of strange matter	Witten (1984), Madsen et al. (1986), Madsen (1988), Alcock et al. (1988)
Strange matter as compact energy source	Shaw et al. (1989)
Strangelets in nuclear collisions	Liu et al. (1984), Greiner et al. (1987), Greiner et al. (1988)

Table 1: *Overview of strange matter phenomenology*

the surface of the strange star, a crust of nuclear material, which it polarizes (Alcock, Farhi, and Olinto, 1986). The maximal possible density at the base of the crust (inner crust density) is determined by neutron drip, which occurs at about 4.3×10^{11} g/cm^3. (Free neutrons in the star cannot exist. These would be dissolved into quark matter as they gravitate into the strange core. Therefore the maximum density of the crust is strictly limited by neutron drip.)

The determination of the electrostatic electron potential at the surface of a strange star performed by Alcock, Farhi, and Olinto (1986) has been extended to finite temperatures only recently (Kettner, Weber, Weigel, and Glendenning, 1995a). The results obtained there for the gap between the surface of the star's strange core and the base of the inner crust are shown in Fig. 2. A minimum value of $R_{\rm gap} \sim 200$ fm was established by Alcock, Farhi, and Olinto (1986) as the lower bound on $R_{\rm gap}$ necessary to guarantee the crust's security against strong interactions with the strange-matter core. For this value one finds from Fig. 2 that a hot strange pulsar with $T \sim 30$ MeV can only carry nuclear crusts whose electrostatic potential at the base is rather smaller, $eV_{\rm crust} \lesssim 0.1$ MeV. Crust potentials in the range of 8–12 MeV, which are expected for a crust at neutron drip density (Alcock, Farhi, and Olinto, 1986), are only possible for

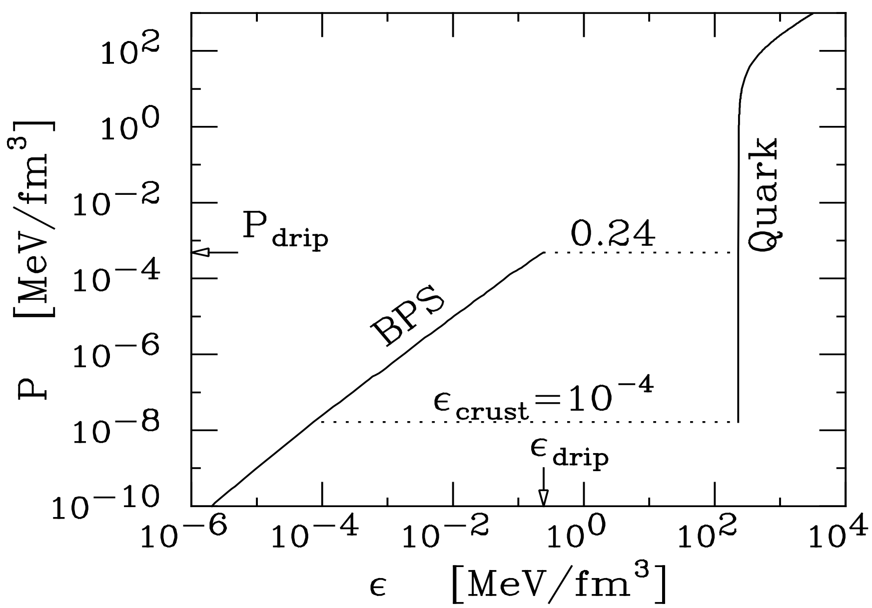

Figure 3: *Equation of state of a strange star surrounded by a nuclear crust.* $P_{\rm drip}(\epsilon_{\rm drip})$ *denotes the pressure at the maximum possible inner crust density determined by neutron drip,* $\epsilon_{\rm crust} = 0.24$ MeV/fm^3*. Any inner crust value smaller than that is possible. As an example, we show the equation of state for* $\epsilon_{\rm crust} = 10^{-4}$ MeV/fm^3*.*

core temperatures of $T \lesssim 5$ MeV. Therefore we conclude that only strange stars with rather low temperatures (on the nuclear scale) can carry the densest possible crusts.

4 Equation of state of strange stars with crust

The somewhat complicated situation of the structure of a strange star with crust described above can be represented by a proper choice of equation of state (Glendenning and Weber, 1992), which consists of two parts (Fig. 3). At densities below neutron drip it is represented by the low-density equation of state of charge-neutral nuclear matter, for which we use the Baym-Pethick-Sutherland equation of state. The star's strange-matter core is described by the bag model (Freedman and McLerran, 1977; Farhi and Jaffe, 1984; Glendenning and Weber, 1992; Kettner, Weber, Weigel, and Glendenning, 1995a).

5 Properties of strange-matter stars

5.1 Complete sequences of strange-satter stars

Since the nuclear crusts surrounding the cores of strange stars are bound by the gravitational force rather than confinement, the mass-radius relationship of strange-matter stars with crusts is qualitatively similar to the one of purely gravitationally bound stars – i.e., neutron stars and white dwarfs – as illustrated in Fig. 4. The strange-star

Experiment	References
Cosmic ray searches for strange nuggets:	
balloon-borne experiments	Saito (1990, 1995)
MACRO	MACRO (1992)
IMB	De Rújula et al. (1983)
tracks in ancient mica	De Rújula et al. (1984)
	Price (1984)
Rutherford backscattering of ^{238}U and ^{208}Pb	Brügger et al. (1989)
Heavy-ion experiments at BNL: E864, E878, E882-B, E886, E-888, E896-A	Thomas et al. (1995)
Heavy-ion experiments at CERN: NA52	Thomas et al. (1995)

Table 2: *Overview of search experiments for strange matter*

Features of strange quark-matter stars	observable	definite signal
• Strange Stars:		
Small rotational periods, $P < 1$ msec	yes †	possibly
• Light, planetary-like objects	yes	no
• Strange Dwarfs (white-dwarf-like)	yes	to be studied *
• Cooling behavior	yes	possibly
• Glitches	yes	to be studied *
• Post-glitch behavior	yes	to be studied *

Table 3: *Features of strange quark-matter stars.(†Until recently rotational periods of $P \sim 1$ millisecond were the borderline of detectability. *Presently under investigation.)*

sequence is computed for the maximal possible inner crust density, $\epsilon_{\rm crust} = \epsilon_{\rm drip}$. Of course there are other possible sequences of strange stars with any smaller value of inner crust density. Their properties were discussed by Glendenning, Kettner and Weber (1995a,b). From the maximum-mass star (dot), the central density decreases monotonically through the sequence in each case. The neutron-star sequence is computed for a representative model for the equation of state of neutron star matter, the relativistic Hartree-Fock equation of state (HFV of Weber and Weigel, 1989), which has been combined at subnuclear densities with the Baym-Pethick-Sutherland equation of state. Hence the white dwarfs shown in Fig. 4 are computed for the latter. (For an overview of the bulk properties of neutron stars, constructed for a representative collection of modern nuclear equations of state, we refer to Weber and Glendenning (1992, 1993a,b).) Those gravitationally bound stars with radii $\lesssim 200$ km and $\gtrsim 3000$ km represent stable neutron stars and white dwarfs, respectively. The fact that strange stars with crust possess smaller radii than neutron stars leads to smaller rotational mass shedding (Kepler) periods $P_{\rm K}$, as indicated by the classical expression $P_{\rm K} = 2\pi\sqrt{R^3/M}$. (We recall that mass shedding sets an absolute limit on rapid rotation.) Of course the general relativistic expression for $P_{\rm K}$, given by (Glendenning and Weber, 1992; Glendenning,

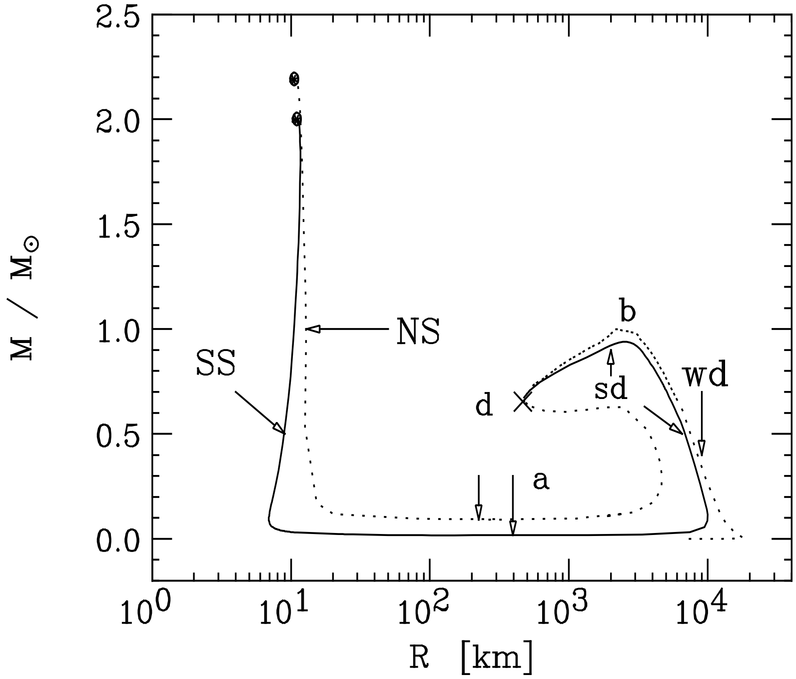

Figure 4: *Mass versus radius of strange-star configurations with nuclear crusts (solid curve) and gravitationally bound stars (dotted). (NS=neutron star, SS=strange star, wd=white dwarf, sd=strange dwarf.) The cross denotes the termination point of the strange-dwarf sequence ($\epsilon_{\rm crust} = \epsilon_{\rm drip}$). The dots and vertical arrows refer to the maximum- and minimum-mass star of each sequence.*

Kettner, and Weber, 1995a)

$$P_{\rm K} \equiv \frac{2\,\pi}{\Omega_{\rm K}}\,, \text{ with } \ \Omega_{\rm K} = \omega + \frac{\omega'}{2\psi'} + e^{\nu-\psi}\sqrt{\frac{\nu'}{\psi'} + \Big(\frac{\omega'}{2\psi'}e^{\psi-\nu}\Big)^2}\,, \tag{1}$$

which is to be applied to neutron and strange stars, is considerably more complicated. However the qualitative dependence of $P_{\rm K}$ on mass and radius remains valid (Glendenning and Weber, 1994). So one finds that, due to the smaller radii of strange stars, the complete sequence of such objects (and not just those close to the mass peak, as is the case for neutron stars) can sustain extremely rapid rotation (Glendenning, Kettner, and Weber, 1995a). In particular, a strange star with a typical pulsar mass of $\sim 1.45\,M_\odot$ can rotate at (general relativistic) Kepler periods as small as $P \simeq 0.5$ msec, depending on crust thickness and bag constant (Glendenning and Weber, 1992; Glendenning, Kettner, and Weber, 1995a). This is to be compared with $P_{\rm K} \sim 1$ msec obtained for neutron stars of the same mass (Weber and Glendenning, 1993a,b).

The minimum-mass configuration of the strange-star sequence (labeled 'a' in Fig. 4) has a mass of about $M_{\rm min} \sim 0.017\,M_\odot$ (about 17 Jupiter masses). More than that, we find stable strange-matter stars that can be even by orders of magnitude lighter than this star, depending on the chosen value of inner crust density (Glendenning, Kettner, and Weber, 1995a,b). If abundant enough in our Galaxy, such low-mass strange stars, whose masses and radii resemble those of ordinary planets (hence one

may call such objects strange planets, or strange MACHOS) could be seen by the gravitational microlensing searches that are being performed presently. Strange stars located to the right of 'a' consist of small strange cores ($R_{\rm core} \lesssim 3$ km) surrounded by a thick nuclear crust (made up of white dwarf material). We thus call such objects strange dwarfs. Their cores have shrunk to zero at 'd'. What is left is a ordinary white dwarf with a central density equal to the inner crust density of the former strange dwarf (Glendenning, Kettner, and Weber, 1995a,b). A detailed stability analysis of strange stars against radial oscillations (Kettner, Weber, Weigel, and Glendenning, 1995a,b) shows that the strange dwarfs between 'b' and 'd' in Fig. 4 are unstable against the fundamental eigenmode. Hence such objects cannot exist stably in nature. However all other stars of this sequence ($\epsilon_{\rm crust} = \epsilon_{\rm drip}$) are stable against oscillations. So, in contrast to neutron stars and white dwarfs, the branches of strange stars and strange dwarfs are stably connected with each other (Glendenning, Kettner, and Weber, 1995a,b). So far our discussion was restricted to inner crust densities equal to neutron drip. For the case $\epsilon_{\rm crust} < \epsilon_{\rm drip}$, we refer to Glendenning, Kettner, and Weber (1995a).

5.2 Glitch behavior of strange pulsars

A crucial astrophysical test, which the strange-quark-matter hypothesis must pass in order to be viable, is whether strange quark stars can give rise to the observed phenomena of pulsar glitches. In the crust quake model an oblate solid nuclear crust in its present shape slowly comes out of equilibrium with the forces acting on it as the rotational period changes, and fractures when the built-up stress exceeds the sheer strength of the crust material. The period and rate of change of period slowly heal to the trend preceding the glitch as the coupling between crust and core re-establish their co-rotation.

The only existing investigation which deals with the calculation of the thickness, mass and moment of inertia of the nuclear solid crust that can exist on the surface of a rotating, general relativistic strange quark star has been performed by Glendenning and Weber (1992). Their calculated mass-radius relationship for strange stars with a nuclear crust, whose maximum density is the neutron drip density, is shown in Fig. 5. The radius of the strange quark core, denoted $R_{\rm drip}$, is shown by the dashed line, $R_{\rm surf}$ displays the star's surface. (A value for the bag constant of $B^{1/4} = 160$ MeV for which 3-flavor strange matter is absolutely stable has been chosen. This choice represents weakly bound strange matter with an energy per baryon ~ 920 MeV, and thus corresponds to strange quark matter being absolutely bound with respect to ^{56}Fe). The radius of the strange quark core is proportional to $M^{1/3}$ which is typical for self-bound objects. This proportionality is only modified near that stellar mass where gravity terminates the stable sequence.

The moment of inertia of the hadronic crust, $I_{\rm crust}$, that can be carried by a strange star as a function of star mass for a sample of rotational frequencies of $\Omega = \Omega_{\rm K}, \Omega_{\rm K}/2$ and 0 is shown in Fig. 6. Because of the relatively small crust mass of the maximum-mass models of each sequence, the ratio $I_{\rm crust}/I_{\rm total}$ is smallest for them (solid dots in Fig. 6). The less massive the strange star the larger its radius (Fig. 5) and therefore the larger both $I_{\rm crust}$ as well as $I_{\rm total}$. The dependence of $I_{\rm crust}$ and $I_{\rm total}$ on M is such that their ratio $I_{\rm crust}/I_{\rm total}$ is a monotonically decreasing function of M. One sees that there is only a slight difference between $I_{\rm crust}$ for $\Omega = 0$ and $\Omega = \Omega_{\rm K}/2$.

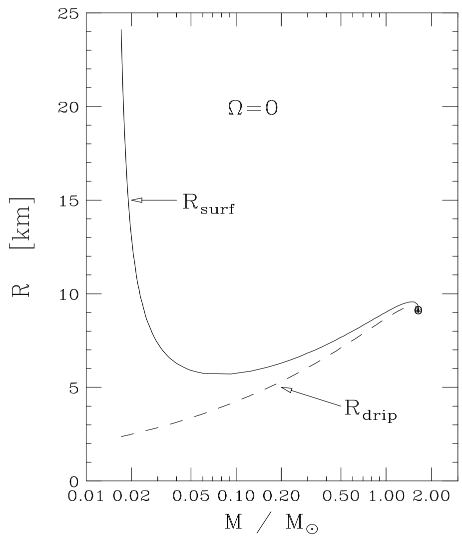

Figure 5: *Radius as a function of mass of a non-rotating strange star with crust (Glendenning et al, 1992).*

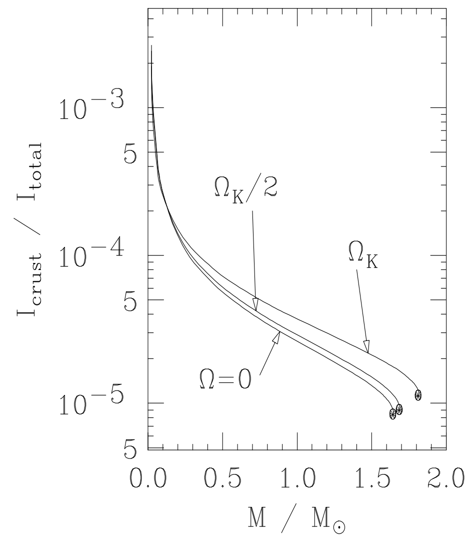

Figure 6: *The ratio $I_{\rm crust}/I_{\rm total}$ as a function of star mass. Rotational frequencies are shown as a fraction of the Kepler frequency, $\Omega_{\rm K}$ (Glendenning et al, 1992).*

Of considerable relevance for the question of whether strange stars can exhibit glitches in rotation frequency, one sees that $I_{\rm crust}/I_{\rm total}$ varies between 10^{-3} and $\sim 10^{-5}$ at the maximum mass. If the angular momentum of the pulsar is conserved in the quake then the relative frequency change and moment of inertia change are equal, and one arrives at (Glendenning and Weber, 1992)

$$\frac{\Delta\Omega}{\Omega} \;=\; \frac{|\Delta I|}{I_0} \;>\; \frac{|\Delta I|}{I} \;\equiv\; f\,\frac{I_{\rm crust}}{I} \;\sim\; (10^{-5} - 10^{-3})\,f\;,\;\text{with}\quad 0 < f < 1\,. \qquad (2)$$

Here I_0 denotes the moment of inertia of that part of the star whose frequency is changed in the quake. It might be that of the crust only, or some fraction, or all of the star. The factor f in Eq. (2) represents the fraction of the crustal moment of inertia that is altered in the quake, i.e., $f \equiv |\Delta I|/I_{\rm crust}$. Since the observed glitches have relative frequency changes $\Delta\Omega/\Omega = (10^{-9} - 10^{-6})$, a change in the crustal moment of inertia of $f \lesssim 0.1$ would cause a giant glitch even in the least favorable case (for more details, see Glendenning and Weber, 1992). Moreover, we find that the observed range of the fractional change in the spin-down rate, $\dot\Omega$, is consistent with the crust having the small moment of inertia calculated and the quake involving only a small fraction f of that, just as in Eq. (2). For this purpose we write (Glendenning and Weber, 1992)

$$\frac{\Delta\dot\Omega}{\dot\Omega} \;=\; \frac{\Delta\dot\Omega/\dot\Omega}{\Delta\Omega/\Omega}\,\frac{|\Delta I|}{I_0} \;=\; \frac{\Delta\dot\Omega/\dot\Omega}{\Delta\Omega/\Omega}\,f\,\frac{I_{\rm crust}}{I_0} \;>\; (10^{-1}\text{ to }10)\,f\;, \qquad (3)$$

where use of Eq. (2) has been made. Equation (3) yields a small f value, i.e., $f < (10^{-4}$ to $10^{-1})$, in agreement with $f \lesssim 10^{-1}$ established just above. Here measured

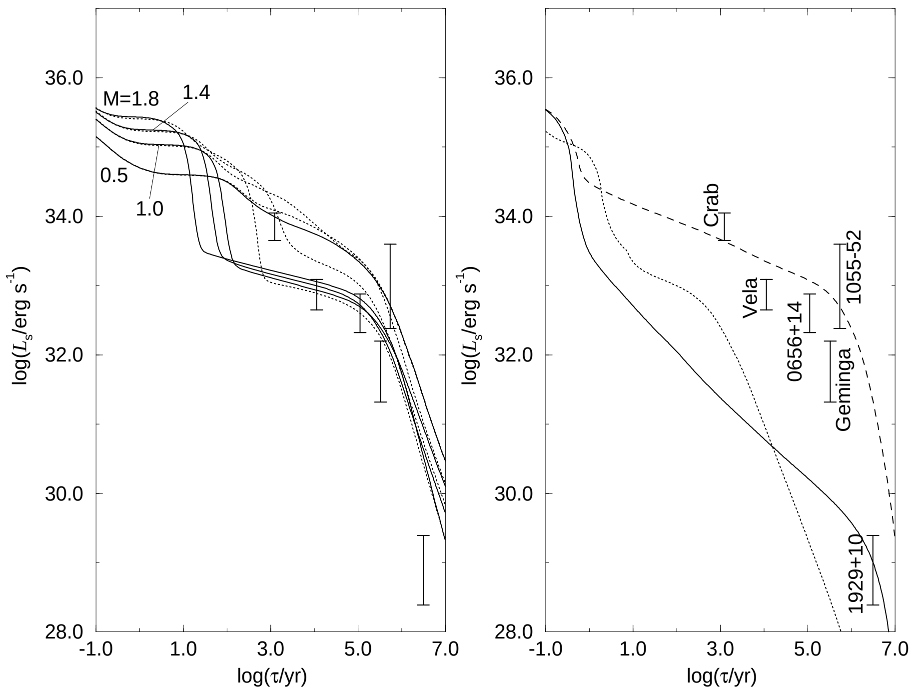

Figure 7: *Left panel: Cooling of neutron stars with pion (solid curves) or kaon condensates (dotted curve). Right panel: Cooling of $M = 1.8\, M_\odot$ strange stars with crust. The cooling curves of lighter strange stars, e.g. $M \gtrsim 1\, M_\odot$, differ only insignificantly from those shown here. Three different assumptions about a possible superfluid behavior of strange quark matter are made: no superfluidity (solid), superfluidity of all three flavors (dotted), and superfluidity of up and down flavors only (dashed). The vertical bars denote luminosities of observed pulsars.*

values of the ratio $(\Delta\Omega/\Omega)/(\Delta\dot{\Omega}/\dot{\Omega}) \sim 10^{-6}$ to 10^{-4} for the Crab and Vela pulsars, respectively, have been used. So we arrive at the important finding that the nuclear crust mass that can envelope a strange matter core can be sufficiently large enough such that the relative changes in Ω and $\dot{\Omega}$ obtained for strange stars with crust in the framework of the crust quake model are consistent with the observed values, in contrast to claims expressed in the literature.

6 Cooling behavior of neutron stars and strange stars

The left panel of Fig. 7 shows a numerical simulation of the thermal evolution of neutron stars. The neutrino emission rates are determined by the modified and direct Urca processes, and the presence of a pion or kaon condensate. The baryons are treated as superfluid particles. Hence the neutrino emissivities are suppressed by an exponential factor of $\exp(-\Delta/kT)$, where Δ is the width of the superfluid gap (see Schaab, Weber, Weigel, and Glendenning (1996) for details). Due to the dependence of the direct Urca process and the onset of meson condensation on star mass, stars that

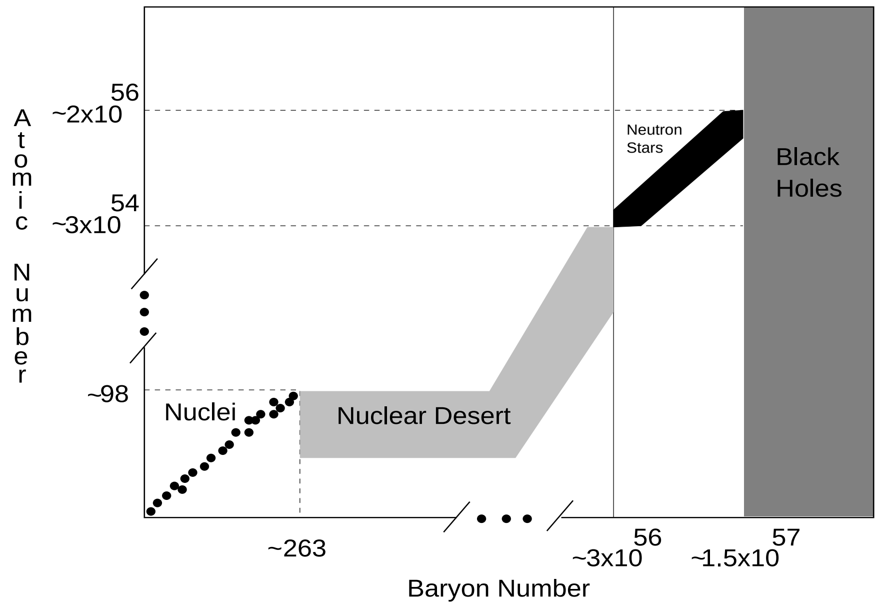

Figure 8: *Graphical illustration of all possible stable nuclear objects if nuclear matter (i.e., iron) is the most stable form of matter. Note the huge range referred to as nuclear desert which is void of any stable nuclear systems.*

are too light for these processes to occur (i.e., $M < 1\,M_\odot$) are restricted to standard cooling via modified Urca. Enhanced cooling via the other three processes results in a sudden drop of the star's surface temperature after about 10 to 10^3 years after birth, depending on the thickness of the ionic crust. As one sees, agreement with the observed data is achieved only if different masses for the underlying pulsars are assumed. The right panel of Fig. 7 shows cooling simulations of strange quark stars. The curves differ with respect to assumptions made about a possible superfluid behavior of the quarks. Because of the higher neutrino emission rate in non-superfluid quark matter, such quark stars cool most rapidly (as long as cooling is core dominated). In this case one does not get agreement with most of the observed pulsar data. The only exception is pulsar PSR 1929+10. Superfluidity among the quarks reduces the neutrino emission rate, which delays cooling (Schaab, Weber, Weigel, and Glendenning, 1996). This moves the cooling curves into the region where most of the observed data lie.

Subject to the inherent uncertainties in the behavior of strange quark matter as well as superdense nuclear matter, at present it appears much too premature to draw any definitive conclusions about the true nature of observed pulsars. Nevertheless, should a continued future analysis in fact confirm a considerably faster cooling of strange stars relative to neutron stars, this would provide a definitive signature (together with rapid rotation) for the identification of a strange star. Specifically, the prompt drop in temperature at the very early stages of a pulsar, say within the first 10 to 50 years after its formation, could offer a good signature of strange stars (Pizzochero, 1991). This feature, provided it withstands a more rigorous analysis of the microscopic properties of quark matter, could become particularly interesting if continued observation of SN 1987A would reveal the temperature of the possibly existing pulsar at its center.

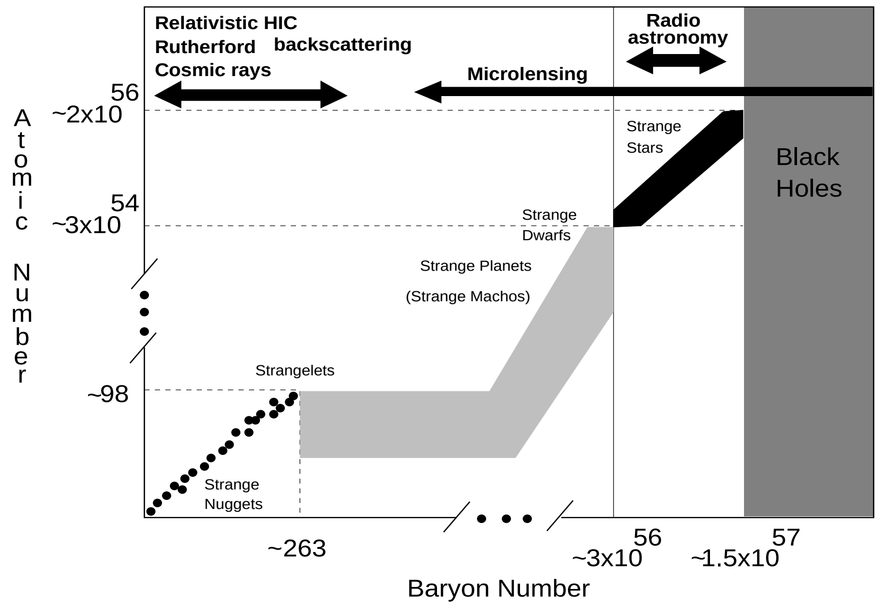

Figure 9: *Same as Fig. 8 but for strange quark matter as the most stable configuration of matter. Various stable strange-matter objects are shown. In sharp contrast to Fig. 8, the nuclear desert does not exist anymore but is filled with a variety of different stable strange-matter objects, ranging from strangelets at the small baryon number end to strange dwarfs at the large baryon number end. The strange counterparts of ordinary atomic nuclei are denoted strange nuggets, those of neutron stars (pulsars) are referred to as compact strange stars (see text for details). Observational implications are indicated at the top.*

7 Summary

This work deals with an investigation of the properties of the complete sequences of strange-matter stars that carry nuclear crusts. Some striking features of such objects are summarized in Table 3. Figures 8 and 9 stress the implications of strange quark matter as the most stable form of matter graphically. The following items are particularly noteworthy:

1. The complete sequence of compact strange stars can sustain extremely rapid rotation and not just those close to the mass peak, as is the case for neutron stars!

2. If the strange matter hypothesis is correct, the observed white dwarfs and planets could contain strange-matter cores in their centers. The baryon numbers of their cores are smaller than $\lesssim 2 \times 10^{55}$!

3. The strange stellar configurations would populate a vast region in the mass-radius plane of collapsed stars that is entirely void of stars if strange quark matter is not the absolute ground state of strongly interacting matter!

4. If the new classes of stars mentioned in (2) and (3) exist abundantly enough in our Galaxy, the presently performed gravitational microlensing experiments could see them all!

5. We find that the moment of inertia of the crust on a strange star can account for both the observed relative frequency changes of pulsars (glitches) as well as the relative change in spin-down rate!

6. Due to the uncertainties in the behavior of superdense nuclear as well as strange matter, no definitive conclusions about the true nature (strange or conventional) of observed pulsar can be drawn from cooling simulations yet. As of yet they could be made of strange quark matter as well as of conventional nuclear matter.

Of course, there remain various interesting aspects of strange pulsars, strange dwarfs and strange planets that need to be worked out in detail. From their analysis one may hope to arrive at definitive conclusions about the behavior of superdense nuclear matter and, specifically, the true ground state of strongly interacting matter. Clarifying the latter item is of fundamental importance for the early universe, its evolution to the present day, massive stars, and laboratory physics.

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